

Mixed Layer Response to Monsoonal Surface Forcing in the Arabian Sea

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Award Number: N00014-94-1-0161
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LONG-TERM GOALS

Our long-range scientific objectives are to observe and understand the temporal and spatial variability of the upper ocean and to identify the role of air-sea interaction in determining that variability. We seek to do this over a wide range of environmental conditions in order to improve our understanding of upper ocean dynamics and of the physical processes that determine the vertical and horizontal structure of the upper ocean.

OBJECTIVES

Prior to the Arabian Sea Mixed Layer Dynamics Experiment, efforts to observe and understand air-sea interaction and upper ocean variability had never been made in a region characterized by strong, sustained forcing; and the separation of oceanic variability due to atmospheric forcing from that associated with mesoscale variability has been difficult. The combination of strong, sustained monsoonal forcing and mesoscale variability associated with eddies and coastal jets characteristic of the Arabian Sea presented a unique opportunity to add to our understanding of the upper ocean response to atmospheric forcing.

Objectives of the field experiment were to test these ideas: the upper ocean physical and biological response are largely one-dimensional; Ekman pumping velocities significantly affect the mixed layer evolution; summer mixed layer cooling results from one or a combination of increased cloud cover, large latent heat loss, lateral advection of coastally-upwelled water, open-ocean upwelling, and entrainment; entrainment is dominated by shears associated with sub-inertial wind-driven flow; and mesoscale variability provides the primary source of vertical circulation at the base of the mixed layer. In continuing work, our objective has been to additionally test the following hypotheses: three-dimensional flow divergences due to high-frequency and small spatial structure in the wind field are important in the vertical velocity field at the base of the mixed layer, diurnal cycling during the NE monsoon produces a horizontally homogeneous mixed layer, resolution of high frequency wind and diurnal heat forcing significantly modifies the large-scale heat transport, and additional upwelling and vertical mixing associated with the mesoscale contributes significantly to the evolution of the mixed layer.

APPROACH

As a part of the ONR-sponsored Arabian Sea Mixed Layer Dynamics experiment we deployed an array of surface and subsurface mooring in cooperation with Rudnick (SIO), Eriksen (UW), Dickey (USC), and Marra (LDEO), from October 1994 - October 1995, just south of the climatological maximum of the Findlater jet in the north-central Arabian Sea. The observations showed that there were errors in some widely used flux climatologies, and showed striking differences in the surface forcing between the NE monsoon (November-January), characterized by moderate wind forcing and strong oceanic surface heat and freshwater loss, and the SW monsoon (June-August), with strong winds, significant oceanic heat gain, and reduced evaporation. The mixed layer was observed to cool and deepen during each monsoon, driven primarily by convection during the NE monsoon and wind-driven mixing during the SW monsoon. Mesoscale variability was the major signal in the velocity record, and provided significant horizontal heat fluxes.

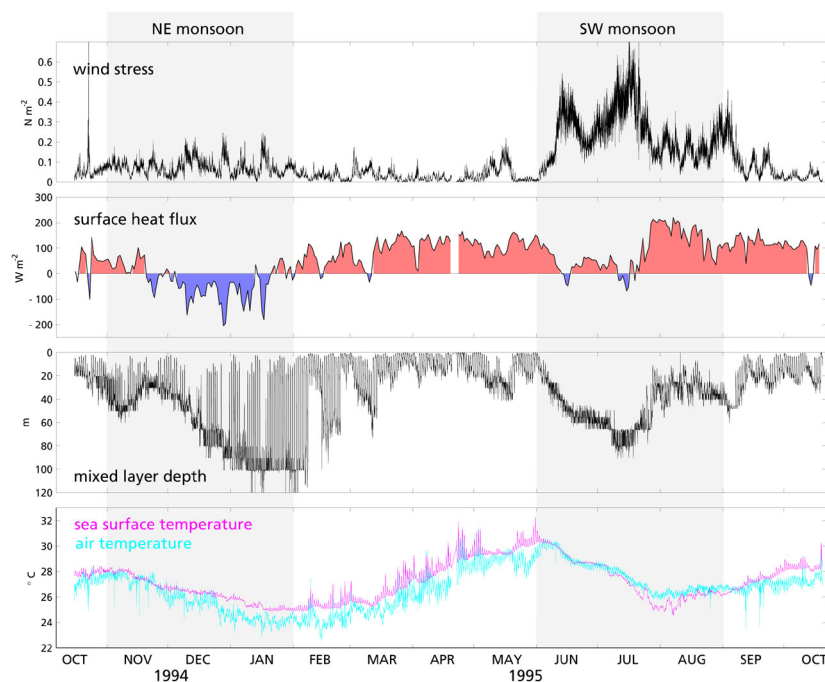


Figure 1: An overview of the data from the Arabian Sea central (WHOI) mooring. From top to bottom: the wind stress, the net surface heat flux, the mixed layer depth determined from a 0.1°C difference from sea surface temperature (SST) criterion, and the air and sea surface temperatures.

Analysis has had two major thrusts. First, quantitative descriptions of the upper ocean response were developed, including heat budgets and identification of the relative roles of various physical processes. Second, one- and three-dimensional models were used to test our understanding of the response at the site of the moored array and to extend it to the entire Arabian Sea.

WORK COMPLETED

The field program provided an unprecedented look at the response of the mixed layer to the wide range of surface forcing found to be associated with the annual cycle in the Arabian Sea. The effort integrated other data to examine the mesoscale horizontal heat flux and to investigate the effect of the diurnal cycle on the mixed layer in one- and three-dimensional models. Graduate student Albert

Fischer (MIT/WHOI Joint Program) completed his Ph.D. work in August on this material, working with Weller as advisor.

A quantitative analysis of the upper ocean heat budget at the moored array has been completed. Additional datasets of combined TOPEX/ERS altimetry (courtesy of Leben and Fox, CCAR), satellite SST (JPL), and SeaSoar surveys (Lee, UW/APL) have allowed identification of the dynamic origins of the strong horizontal heat fluxes observed. This work is described in Chapter 2 of *Fischer* (2000), and will be submitted alongside an overview paper describing the oceanic variability observed at the moored array site. A collaboration with Craig Lee used climatological data supplied in part by Simon Josey (SOC) to examine the relative effect of Ekman pumping and locally-driven entrainment on the deepening of the mixed layer across the Arabian Sea (*Lee et al.*, 2000).

The three-dimensional model of *McCreary et al.* (1993, hereafter MKM) was used to investigate the Arabian Sea response to diurnal variability in the solar heat flux, and to high-frequency and high spatial variability wind stress forcing. This work is described in Chapter 3 of *Fischer* (2000), and is in preparation as a paper. The collaboration with Jay McCreary (UH/SOEST) also included model/data comparisons and cooperation in studying the effect of the diurnal cycle on a coupled physical-biological model (*McCreary et al.*, 2000). To further examine how the diurnal cycle affects the vertical mixing and redistribution of heat, the responses of a number of one-dimensional mixed layer models (including the layered formulation in the MKM model; the *Price et al.*, 1996 model, PWP; and the *Large et al.*, 1994 model, KPP) were examined under a wide variety of surface forcing conditions. This work is described in Chapter 4 of *Fischer* (2000).

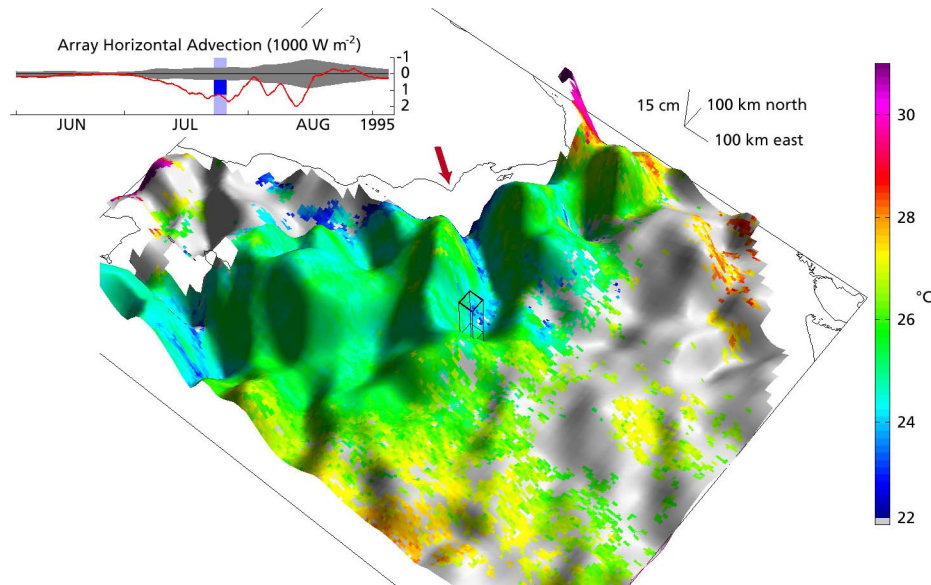


Figure 2: A visualization of three different types of data on 25 July 1995, at the height of the SW monsoon: in the upper left corner the estimated horizontal heat advection at the site of the moored array, satellite-derived sea surface temperature as color, and combined TOPEX/ERS altimetric height anomaly as the height of the surface. The black box marks the site of the moored array in the central Arabian Sea, with the Arabian coastline, and parts of the Somali and Indian coasts marked by black lines. Topography in the sea surface is associated with geostrophic surface flows. The strong horizontal advection observed at the moored array can be traced to the strong offshore export of recently-upwelled water in a filament extending from Ras Madrasah (red arrow).

RESULTS

The field experiment captured the first year-long high quality surface flux and upper ocean record in the Arabian Sea. Strong horizontal advection of water during the SW monsoon, seen in the heat budget of the moored array, was identified using satellite SST imagery and altimetry as being upwelled water from the Omani coast, transported well offshore by a filament (Figure 2). During the NE monsoon, strong horizontal heat advection at the moored array was found to be associated with mesoscale eddies that had been generated in the previous SW monsoon and propagated westward. The altimetric record shows that mesoscale activity is elevated along the Arabian coast during the SW monsoon, suggesting that these coastal filaments play an important role in the offshore transport and mixing of coastally-upwelled water.

The SST and mixed layer depth are observed to respond to high frequency (diurnal to atmospheric synoptic time scales) variability in the surface heat flux and wind stress. The rectified effect of this high frequency forcing was investigated using a three-dimensional reduced gravity thermodynamic model of the Arabian Sea and Indian Ocean (MKM). Both the diurnal cycle and high frequency wind forcing acted locally to increase vertical mixing in the model, reducing the SST. Interactions between the local response to the surface forcing, Ekman divergences, and remotely propagated signals in the model can reverse this, particularly at low latitudes. The annual mean SST, however, is lowered under both diurnal heat and high frequency wind forcing, changing the balance between the net surface heat flux (which is dependent in turn on the SST) and the meridional heat flux in the model.

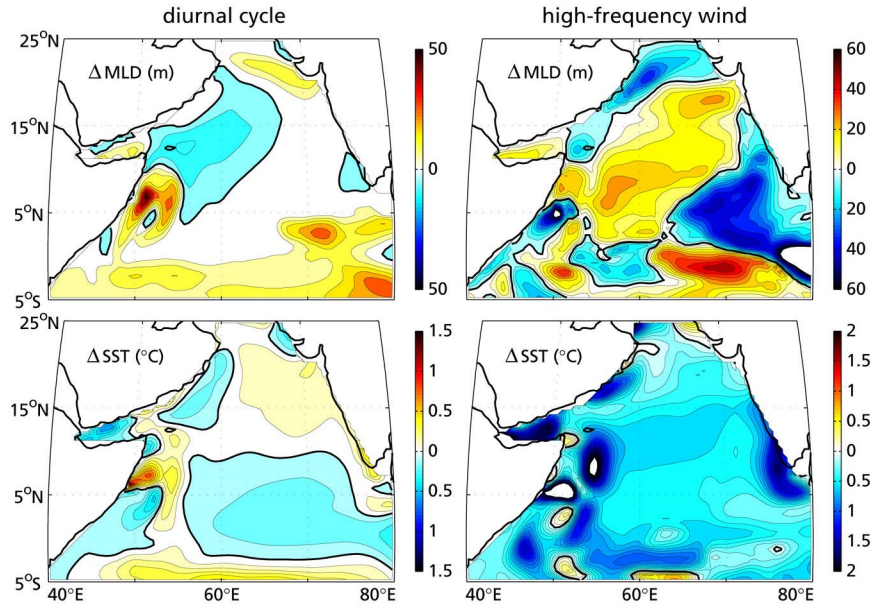


Figure 3: Snapshots of model differences (change in mixed layer depth, top, and sea surface temperature, bottom) when run with the addition of the diurnal cycle in heat (left panels) and with the addition of high frequency (4x daily) resolved winds (right panels), for the SW monsoon.

The additional vertical mixing caused by a resolved wind stress field has been studied (*Large et al.*, 1991; *Chen et al.*, 1999), and can be understood simply based on energetic arguments. While noted before (*Sui et al.*, 1997), the net effect of the diurnal cycle on SST and MLD has not been studied systematically, and cannot be understood as simply. The rectification of the diurnal cycle was explored

across a wide parameter space in net heat and wind forcing using several one-dimensional upper ocean models with different representations of vertical mixing processes. All show increased vertical mixing in response to the diurnal cycle in net heating conditions, but the degree of enhanced mixing is highly dependent on the model formulation used.

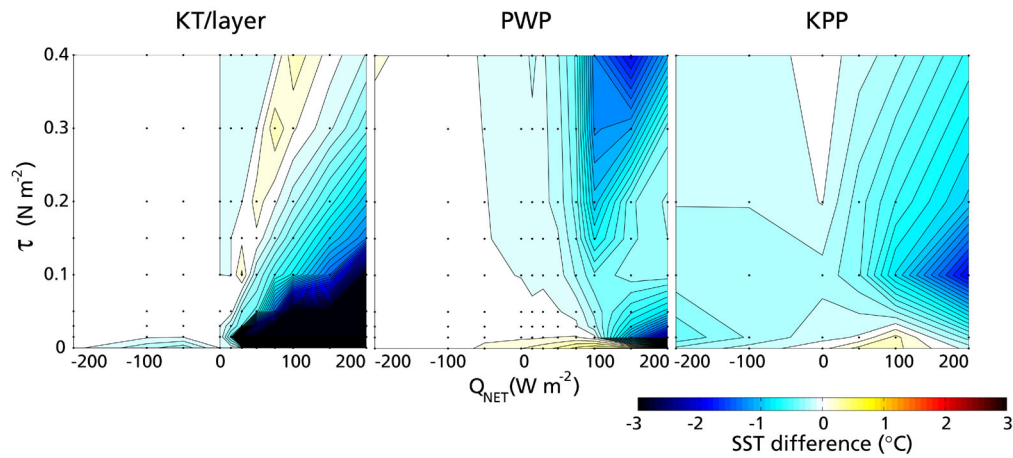


Figure 4: A summary of the differences in SST in diurnally-forced and mean-forced 60-day runs of three one-dimensional mixed layer models, varying the daily average surface heat forcing and the wind forcing. Dots in the parameter space represent the parallel runs used to calculate the difference. Significant differences in SST only occur for net heating, but the sensitivity is very dependent on the model formulation.

IMPACT/APPLICATIONS

The field work produced the first long time series of high quality near-surface meteorology and air-sea fluxes to be obtained in the Arabian Sea. Comparisons with climatology give us confidence in selecting forcing products for ocean models. Observations of the strong cooling heat flux associated with offshore transport give insight into the dynamic mechanisms connecting coastal upwelling and upper ocean cooling. The net effect of the diurnal cycle and the importance of high-frequency wind forcing on the vertical mixing of temperature and on larger-scale circulation changes will be applicable to any modeling study of upper ocean circulation or biology, particularly in regions where mixed-layer diurnal variability is important. The comparison of mixed layer models suggests some simple improvements in the parameterizations could be made in lieu of resolution of the diurnal cycle.

TRANSITIONS

Ongoing cooperation with Kindle (NRL) in modeling should lead to improvement of Navy ocean forecasting models in the region, and has led to confirmation of the quality of FNMOC model winds.

RELATED PROJECTS

This work has resulted in ongoing cooperative projects with numerical modeling (McCreary, SOEST; Kindle, NRL), satellite remote sensing (Leben, Fox, CCAR; Arnone, NRL), as well as with other ONR Arabian Sea investigators (Lee, Brink, Eriksen, Rudnick, Dickey, Marra). The role of mesoscale eddies

in pulses in productivity has been investigated with the aforementioned ONR investigators as well as JGOFS Arabian Sea investigators (Honjo, WHOI; Prell, Brown; Dymond, OSU)

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